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Remarks on Photon-Hadron Interactions

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Abstract

Theoretical aspects of VMD and related approaches to real photon-hadron interaction are discussed. The work relies on special relativity, properties of linearly polarized photons, angular momentum conservation and relevant experiments. It is explained why VMD and similar approaches should not be regarded as part of a theory but, at most, as phenomenological models. A further experiment pertaining to this issue is suggested.

1. Introduction

The discovery of the photon in the early years of the previous century has identified it as a pure electromagnetic object. Many years later it has been observed that hard photons interact with hadrons in a manner which is akin to strong interactions and looks independent of the electric charges of the hadronic target. The following experimental results can be used as an illustration of this conclusion.

The cross section of hard photons scattered from a proton target is practically the same as that of a neutron one (see [1], pp. 292-293). Another kind of data is the ratio between the numbers of hadrons and leptons emitted from a photon-proton interaction region. Here the number of hadrons is greater by four orders of magnitude with respect to the leptonic number. (This point is easily inferred from the data discussed in [2], pp. 1567-1568 and from the table on p. 323 of [1].) Thus, it is concluded that "there is ample evidence which shows that the photon's hadronic structure plays a significant role in its interactions" (see the abstract of [1]).

An approach attempting to explain experimental results of photon-hadron interactions claims that a physical photon is composed of a pure electromagnetic component *and* a hadronic one. According to this claim, the wave function of a physical photon takes the form

$$\mid \gamma > = c_0 \mid \gamma_0 > + c_h \mid h > \tag{1}$$

where $\mid \gamma >$ denotes the wave function of a physical photon, $\mid \gamma_0 >$ denotes the pure electromagnetic component of a physical photon and $\mid h >$ denotes its hadronic component. c_0 and c_h are appropriate numerical coefficients. Relation (1) means that a real photon fluctuates between a pure electromagnetic state and a hadronic one. Moreover, this fluctuation is an *inherent property of the photon and is independent of its distance from the hadronic target*. The relative time allotted to each state is proportional to the absolute value of the square of the corresponding coefficient of (1). This approach takes several ramifications, many of which are known as Vector Meson Dominance (VMD) or Vector Dominance Models (VDM). Here it is assumed that the hadronic part of (1) is a neutral vector meson, which has the same spin, parity and charge conjugation quantum numbers as the photon (see eg. eq (2.1) on p. 271 of [1] and eq. (10.104) on p. 298 of [3]). A related claim states that $\mid h >$, the hadronic part of (1), may belong to a larger set of hadronic states[4]. All these approaches are called below Photon's Hadronic Structure Approaches (PHSA). The present work examines critically the theoretical meaning of the common idea of PHSA, which is manifested in (1).

A brief discussion of common properties and of differences between the notions of a theory and a model is helpful for a clarification of the main point of this work. The distinction presented below between these notions should be regarded as a suggestion which is useful for the case discussed here. Obviously, other definitions may be used, if they look helpful in other circumstances.

The following properties are common to a theory and to a model.

A. Both provide a scheme leading to mathematical formulas which describe experimental data. The scheme should be mathematically selfconsistent.

B. Both are acceptable within an appropriate domain of validity. (See [5] for a discussion of the notion of a validity domain of a theory.)

C. Both require a knowledge of certain constants which are determined experimentally.

On the other hand, the following properties distinguish between a theory and a model.

D. Within the corresponding validity domain, prediction of a theory should be very precise whereas a model is acceptable even if it yields just reasonably approximate predictions.

E. The physical constants used in a theory can be determined by means of any set of experiments, provided they are carried out within the theory's validity domain. Another aspect of this point is that in the case of a theory, after fixing the required constants, one can apply *extrapolation*, into far regions, provided they are included in the theory's validity domain. (Thus, for example, after measuring the mass of a macroscopic body, one may use Newtonian mechanics for all velocities which are much smaller than the speed of light.) Contrary to this, a model is generally useful only within a small domain where its constants have been determined. In other words, a model is useful in cases where *interpolation* is applied and deteriorates as it is extrapolated into far regions.

F. A model is tested by its practical benefit. If problems arise, a model may be improved by an addition of certain corrections. (Thus, for example, the nuclear liquid drop model is improved by an addition of nuclear shell model terms, which account for nuclear magic numbers.) By contrast, a theory is tested by its *correctness*. In other words, a model is regarded as useful or not very useful for certain applications whereas a physical theory can be *refuted* if it does not fit experimental data or well established theories which have been confirmed by many experiments.

It is explained in the rest of this paper why PHSA formulas belong to models and do not constitute a part of a theory. This is probably the common belief of the physical community as seen from the term VDM (Vector Dominance Models) and from its inclusion in the phenomenological sections of PACS and of hep-ph@arXiv.org.

The present work discusses only the theoretical side of PHSA. On the other hand, the problem of its usefulness as a model is beyond the scope of the paper. In the second section it is shown that PHSA is inconsistent with some well established theoretical results. Experiments relevant to this matter are discussed in the third section. Concluding remarks are the contents of the last section. Expressions are written in units where $\hbar = c = 1$. Energy-momentum units are MeV and $f^{-1} \simeq 197 MeV$. The cross section unit is $mb = 0.1\, f^2$.

2. Theoretical Problems of the Photon's Hadronic Structure Approach

Several theoretical difficulties of PHSA are pointed out here.

Let us examine the implications of Lorentz transformations on the coefficients c_0 and c_h of (1). For this end, consider Wigner's analysis of the Poincare group[6,7]. The analysis shows that a massive particle can be regarded as an irreducible representation of this group, characterized by its self mass and spin. Massless particles, like the photon, belong to a special case where spin is replaced by helicity.

This analysis is used in quantum field theory. It proves that photons and hadrons are distinct objects. Since a quantum mechanical state of a particle is characterized by the eigenvalues of the self mass and the spin (or helicity), one concludes that *every term* of its wave function should have the same eigenvalues of these operators. It follows that (1) *cannot* represent a quantum mechanical state of a particle. This conclusion proves that PHSA is inconsistent with relativistic quantum field theory.

Another relativistic point is the behavior of c_0 and c_h under Lorentz transformations. It appears that in PHSA, it is assumed that Lorentz transformations do alter these quantities, because the hadronic part of soft photons is assumed to be negligible (see [3], p. 298). Thus, following this assumption, one does not expect that optical photons (or the black body radiation ones) interact strongly with hadrons. The assumption that the relative size of the coefficients c_0 and c_h of (1) depend on the photon's energy is denoted below as the energy dependence assumption.

It is not clear how the energy dependence assumption is embedded in a relativistic theory. Indeed, assume that one measures energetic photons and finds that for 10% of the time they interact like hadrons and for 90% of the time they interact like pure electromagnetic objects. Moreover, as claimed by PHSA, this ratio is an inherent property of the photon and is independent of its proximity to an hadronic target. Hence, relativity tells us that this ratio must be conserved for Lorentz transformations in general and for a Lorentz transformation into a frame where the photon's energy is small, in particular. This matter can be restated as follows. By their definitions, the coefficients c_0 and c_h of (1) are the transition probabilities from a state of a physical photon to that of a pure electromagnetic one and that of a hadron, respectively. Now, "the transition probability has an invariant physical sense" (see [6], top of p. 150). This outcome is inconsistent with the energy dependence assumption. Experimental aspects of this point are discussed in the next section.

Another issue is related to transverse properties of photons. Thus, let us take a linearly polarized photon moving parallel to the z-axis and its electric field is parallel to the x-axis. Experiments measuring the interactions of such a photon with unpolarized target of protons are discussed below. Properties of linearly polarized photons clearly do not satisfy cylindrical symmetry around the z-axis, because a rotation around this axis alters the direction of its electric and magnetic fields. For photons of this kind, the vector potential $\mathbf{A}$ is parallel to the electric field. Hence, since the interaction term of the electromagnetic Lagrangian density is [8,9]

$$L_{int} = -j^\mu A_\mu, \tag{2}$$

one finds that a linearly polarized photon interacts with matter in a manner which breaks cylindrical symmetry around the z-axis.

Let us turn to the interaction of the assumed hadronic part of this photon. Angular momentum conservation is utilized and calculations carried out below show that, *under this restriction*, the assumed hadronic part of a photon interacts with an unpolarized target in a manner which conserves cylindrical symmetry. Special emphasis is put on the M values of the angular momenta, namely on their projection on the z-axis.

Due to angular momentum conservation, the angular momentum part of the photon's hadronic state should be the same as that of the helicity of the (ordinary) electromagnetic state of the photon. Thus, since we have a linearly polarized photon, its spin part has an equal amount of positive and negative helicity (see [8], pp. 114-116; [9] pp. 273-275 and [10]) and is written as a sum of two terms

$$\mid SM >= (\mid 11 > + \mid 1 -1 >)/\sqrt{2}. \tag{3}$$

Here S denotes spin and M denotes its projection on the z-axis. Due to angular momentum conservation, (3) describes also the spin state of the assumed hadronic part of the photon. Let us examine this state under a rotation by $\pi/2$ around the z-axis. (This rotation exchanges the directions of the undulating electric and magnetic fields of the linearly polarized photon.) Under this rotation, each term of the wave function is multiplied by $e^{-im\phi}$[11]. Thus, in the present case the corresponding factor is $e^{\mp\pi/2} = \mp i$ and we have in the rotated frame

$$\mid SM >_{rot} = -i(\mid 11 > - \mid 1 -1 >)/\sqrt{2}. \tag{4}$$

Comparing (3) with (4), one realizes that, although each of the terms of (3) varies only by a phase factor, *the relative phase of the two terms changes sign.* This property means that cylindrical symmetry is broken if and only if interference between the interactions of the two terms of (3) does not vanish. However, it is shown below that no such interference holds. This result proves that the interaction of the hadronic part of a photon with an unpolarized target of protons is expected to conserve cylindrical symmetry.

Three kinds of angular momenta are involved in the process: that of the assumed hadronic part of the photon, (3), that of a proton at the target (having $s = 1/2$ and $m_s = \pm 1/2$) and the spatial angular momentum between the incoming vector meson and the proton participating in the interaction. Since the linear momentum of the photon and of its assumed associated vector meson is parallel to the z-axis, the projection of the spatial angular momentum on this axis vanishes $(\mathbf{r}\times\mathbf{p})\cdot\mathbf{p}=0$.

Let $M(1)$ and $M(-1)$ denote the overall M value of the projectile-target system, pertaining to the first and the second term on the right hand side of (3), respectively. Following the discussion carried out above, one sums the M values of the three components and obtains

$$M(1) = 1 + (\pm 1/2), \qquad M(-1) = -1 + (\pm 1/2). \tag{5}$$

Thus, since the Hamiltonian operator is a scalar in the 3-dimensional space, interactions of the first term of (3) have no common M value with those of the second term. Therefore, no interference between these interactions takes place and cylindrical symmetry is expected to be conserved.

This discussion shows that a pure electromagnetic linearly polarized photon interacts with matter in a manner which breaks cylindrical symmetry, as seen in (2). On the other hand, the assumed hadronic part of such a photon conserves this symmetry. This result means that a transverse information of the photon, namely - its linear polarization, *disappears* as the physical photon fluctuates into a hadronic state. This property clearly reduces the theoretical appeal of the VMD hypothesis. As shown in the next section, it can also be used in an experimental test of its validity.

3. Experimental Considerations

Let us turn to experimental aspects of the topics discussed in the previous section. First, the behavior of the coefficients c_0 and c_h of (1) under Lorentz transformations is examined. Two alternatives are discussed where the energy dependence assumption holds or fails.

Assume that the energy dependence assumption holds. This assumption is probably made in order to settle problems of expected soft photon interactions with hadrons, which otherwise emerge from the VMD assumption. However, it leads to problems as one takes soft photons and examines them in another inertial frame where these photons are very energetic.

Photon-photon interaction is probably most suitable for this purpose, because, unlike massive targets whose rest frame may look preferential, photons have no rest frame. Consider an inertial frame Σ and two sources of soft photon rays (see fig. 1). Here the photons interact electromagnetically and, as far as the linearity of electrodynamics and Maxwell equations hold, the photon-photon interaction vanishes.

Now, let us examine the process in another frame Σ'. In Σ, Σ' is seen moving parallel to the negative direction of the y-axis and its velocity is not much smaller then the speed of light. Hence, in Σ', the photons emitted from S_1 and S_2 are very energetic. Now, if VMD and (1) hold then these photons should have a hadronic part. Thus, in Σ', the photon-photon interaction is expected to consist of two kinds of dynamical processes. The first one is the pure electromagnetic process which is obtained from a Lorentz transformation of what is found in Σ and yields a null quantity. The second process is the hadron-hadron interaction which should take place under the assumption examined here. This is a contradiction because the percentage of events where photons interact and exchange energy-momentum should be the same in all inertial frames.

The second case is the ordinary quantum mechanical approach where c_0 and c_h of (1) conserve their absolute value under a Lorentz transformation (see [6], top of p. 150). For examining this issue, let us take, for example, the Compton scattering of 1 MeV photon colliding with an electron of a hydrogen atom. In this example, calculations refer to the backwards direction $\theta = \pi$. The Compton process is well known[12]. The angular dependence and the energy of the emitted photon are obtained from the Compton relation

$$k_{out} = \frac{k_{in}}{1 + (2k_{in}/m)sin^2(\theta/2)}. \qquad (6)$$

Putting $k_{in} = 1\ MeV$, $m = 0.511\ MeV$ and $\theta = \pi$, one finds for the scattered photon

$$k_{out} \simeq 0.2 MeV. \qquad (7)$$

The Compton unpolarized cross section is[12]

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{2m^2}\left(\frac{k_{out}}{k_{in}}\right)^2\left(\frac{k_{out}}{k_{in}} + \frac{k_{in}}{k_{out}} - sin^2(\theta/2)\right), \qquad (8)$$

where $\alpha \equiv e^2 \simeq 1/137$. In the present experiment, one finds

$$\frac{d\sigma}{d\Omega}(\theta = \pi) \simeq 6.5mb. \tag{9}$$

Let us turn to the photon-proton interaction. Here, the Compton process (8) can be ignored because the proton/electron mass ratio is about 2000 and the cross-section is smaller by a factor of 1/4000000. On the other hand, if VMD-PHSA holds and the photon has a hadronic component, then one expects another process which is a meson-proton scattering. Since, in this case, the proton's mass is 938 times that of the photon's energy, one should have here a scattering process where the photon's energy is (nearly) conserved.

The effective radius of a meson-proton interaction region is less than $10f$ and the photon's momentum is $1MeV \simeq 1/197f^{-1}$. Hence, one finds that the spatial angular momentum practically vanishes and, in a partial wave analysis, only the S-wave contributes to the process.

A crude estimate of the vector meson-proton cross section can be obtained for the case discussed here from the data on π-proton cross section[13]. Here one finds that in the low energy limit

$$\sigma \simeq 7mb. \tag{10}$$

Relying on a quark count, one concludes that a vector meson-proton cross section is of the same order of magnitude as that of the π-proton one (10). Hence, since we have here an S-wave, the expected differential cross section is obtained from a division of (10) by 4π

$$\frac{d\sigma}{d\Omega} \simeq 0.6mb. \tag{11}$$

Due to the assumption discussed here, where c_h of (1) is not negligible, one compares (11) with the backwards Compton scattering differential cross section (9). Thus, it is found that if this version of VMD-PHSA takes place, then a certain percentage of the photons scattered backwards in an actual Compton experiment should conserve the energy of the incoming photon and violate the Compton relation (6) which yields (7). In other words, for $\theta = \pi$, the Compton scattering yields outgoing photons whose energy is 0.2 MeV, whereas the assumed VMD-PHSA effect should yield 1 MeV ones.

To the best of the author's knowledge, this effect has never been reported. Evidently, due to their energy difference, a distinction between these kinds of scattered photons can be easily made. It is interesting to carry out such a test of VMD-PHSA in an experiment dedicated to this problem.

Another issue is the test of cylindrical symmetry in a scattering process of linearly polarized photons on protons. As shown in the previous section, electrodynamics breaks this symmetry whereas the assumed vector meson is expected to interact with protons in a manner which conserves it. Related experiments have been carried out a long time ago[14-16]. These experiments use linearly polarized photons and measure outgoing pions in γp and γn collisions. The results prove that cylindrical symmetry is not conserved, contrary to what is expected from VMD.

4. Concluding Remarks

This work examines theoretical aspects of VMD and related approaches. It is shown above that VMD can be no more than a phenomenological model. Evidently, if its merits are extended and it is regarded as a part of a theory then it should stand refutation tests. As a matter of fact, results of theoretical and experimental tests show that VMD is inconsistent with some well established theories and with experiments. A further experiment dedicated to this issue can be carried out as discussed in the third section.

Another result of this work is that the hadronic features of real photon-hadron interaction await theoretical interpretation.

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Figure Captions

Figure 1:

Two rays of light are emitted from sources S_1 and S_2 which are located at $x = \pm 1$, respectively. The rays intersect at point O which is embedded in the (x, y) plane.

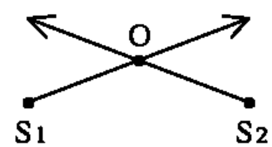

Fig. 1